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COMBUSTION IN SOLID PROPELLANT GRAIN DEFECTS: A STUDY OF BURNING IN SINGLE- AND MULTI-PORE CHARGES

by

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Research Department

June 1977

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FOREWORD

This is an interim summary report describing the pore burning studies conducted during the first year of a fundamental study of high energy propellant safety (HEPS). For a summary of earlier work from this laboratory on flashdown in plastisol-nitrocellulose double-base propellants the reader is referred to Naval Ordnance Test Station Technical Report 3009 dated December 1962, *Flashdown in Solid Propellants*, by Jack L. Prentice.

This work was performed by the Naval Weapons Center during the period January 1976 through March 1977, and was sponsored by the Strategic Systems Project Office under task B0003001.

The author wishes to acknowledge the assistance of Mr. Ray Price in synthesizing the propellants used in this study, and Mr. George Freeman who prepared the porous charges for test. Appreciation is owed Mr. Harold H. Bradley, Jr. for numerous challenging discussions and helpful criticisms during the course of this work and the preparation of the manuscript. Mr. Bradley also suggested the use of mesa propellants (N-5) to test the Andreev criterion. We also thank Mr. Richard Smith for preparing the illustrations for this report and Mr. Don Zurn for performing the arc-image ignition experiments.

This is an informal report containing interim information.

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20 June 1977

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INTRODUCTION

The trend toward very high solids loading in high energy propellants leads to complexities in processing and to greater potential for ballistic anomalies. Present day high energy propellants are often more frangible than their predecessors and physical properties are now found, in many cases, to exert an inordinate effect on combustion. New failure modes are believed to be able to contribute to deflagration-to-detonation transition (DDT). For example, crumbling of a burning grain due to impact or shear represents vastly increased surface area which, if ignited, could lead to detonation. Combustion of porous or frangible charges is therefore of interest to the propulsion community.

This study reduces the problem of convective combustion in porous charges and other grain defects to its ultimate simplicity (viz., the single pore), and then proceeds to reconstruct the more complicated geometrical and combustion situations leading to the porous bed or highly cracked (i.e., spiderweb) propellant. Flashdown (one of the more dramatic types of convective combustion), may be defined as runaway combustion rates (and pressures) associated with flame propagation into grain defects such as ducts, fissures, annuli, pores, etc. This type of anomalous combustion leads to flame spreading rates many orders of magnitude greater than normal. Pressures and pressurization rates exceeding design limits are common where such phenomena occur.

In the combustion of any porous bed, the properties of the bed are characterized by several parameters including pore size. Anomalous (convective) combustion begins in such a system with a single pore. It is not known for certain whether mean pore size or smallest pore size is the governing parameter. Thus, one must ultimately know the conditions necessary to ignite the single pore and to propagate a flame to other pores. Studies on such complex systems as convective burning in damaged, <u>opaque</u> propellant represent a challenge very often quite beyond the capabilities of current diagnostic tools. This study builds from a fundamental base in all these areas.

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EXPERIMENTAL

APPROACH

The approach of this investigation has been to study the flashdown phenomenon in various grain defects, in various propellants, over a range of pressures common in rocketry. The various geometries examined range from single blind and open pores, through multiple blind and open pores, to porous propellants (foamed binders) as well as combustion in annuli. These studies are aimed at defining the necessary and sufficient conditions for onset of flashdown into grain defects. Since the usual cinephotography employed in propellant combustion studies is inadequate for problems of this sort, other diagnostics must be developed or adapted as one goes along. We have adapted an acoustic emission technique from non-destructive testing which is called vibrational response spectroscopy (VRS) in this laboratory.[2,3] This VRS is a new and novel combustion diagnostic technique made necessary by the requirement to characterize combustion within opaque propellants. Beginning with simple propellant test geometry and learning to interpret VRS data for relatively simple types of anomalous combustion creates the confidence in the technique needed later to interpret complex phenomena.

TECHNIQUE

The VRS technique employs accelerometers (Endevco type 2221D) to sense the acoustic emission from the burning propellant strand. The VRS signal is amplified and recorded on tape for later analysis. For the purposes of this study the root-mean-square VRS signal was used as a go/no-go criterion to establish the presence or absence of flashdown. Further analysis of the fine structure of the spectra is being done in a companion program.[2] A block diagram of the system is shown in Figure 1.

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[1]Naval Ordnance Test Station. *Flashdown in Solid Propellants*, by Jack L. Prentice. China Lake, Calif., NOTS, December 1962. (NOTS TP 3009, NAVWEPS Report 7964, publication UNCLASSIFIED.)

[2]Naval Weapons Center. *Vibrational Response Spectroscopy: Extension of Acoustic Emission Techniques to Combustion Diagnostic Use*, by John L. Eisel. China Lake, Calif., NWC, April 1977. (NWC TM 3070, publication UNCLASSIFIED.)

[3]R. L. Geisler, and others, AFRPL. August 1975. (U.S. Patent 3,899,919, UNCLASSIFIED.)

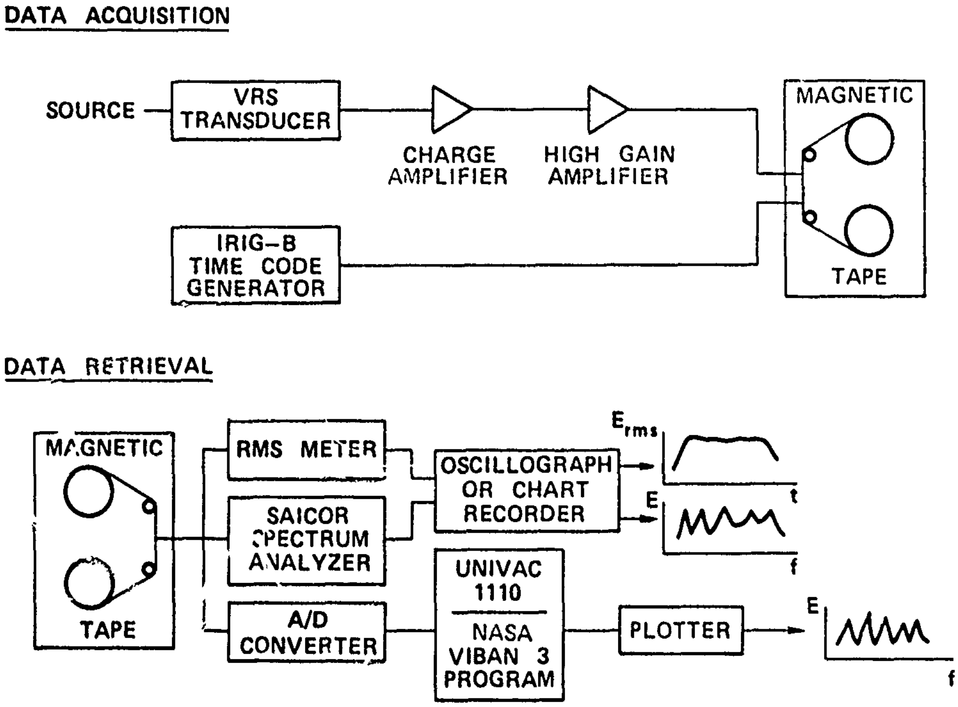

FIGURE 1. Block Diagram of System for Vibrational Response Spectroscopy.

APPARATUS

The combustion bomb is a heavy wall, windowless, stainless steel vessel with a volume of 2190 cm^3. The loading density during these tests was 0.0022 g/cm^3. A schematic of the strand burner is shown in Figure 2, where the relationship of the propellant to the VRS transducer may be seen. In all these studies the VRS transducer is simply cemented to the exterior of the bomb head where it remains throughout the whole program.

For purposes of familiarization with the VRS technique a series of simple strand geometries was chosen (Figure 3) and tests were begun on some newly formulated plastisol-nitrocellulose double-base propellant matching that used in prior work in this laboratory.[1] Tests were initiated with strand geometries known definitely to flashdown (Figure 3b, d) and those known definitely not to flashdown (Figure 3a). Ignition in all cases was by hot wire and the bomb was pressurized with nitrogen. The outer surface of all strands was inhibited with a heavy coat of silicone grease to prevent flashdown except on interior pore walls.

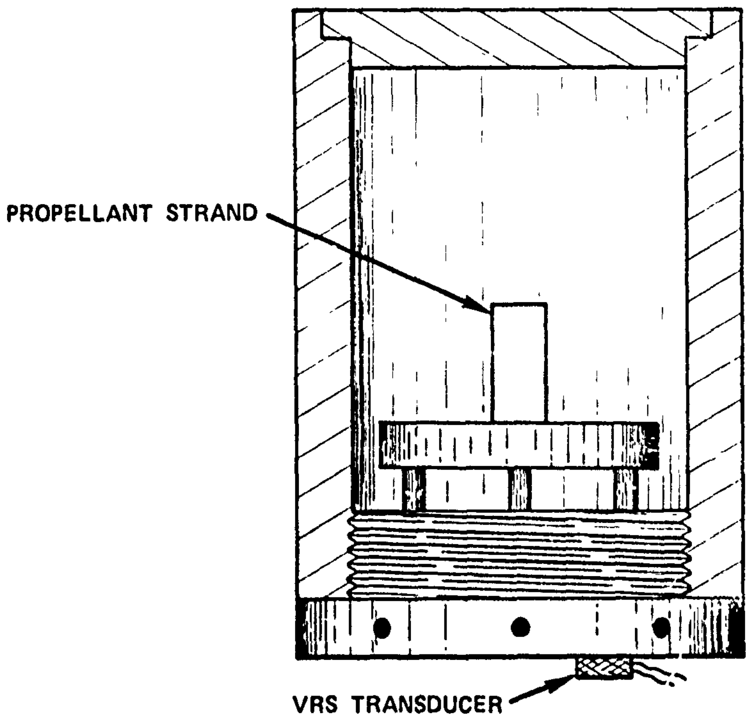

FIGURE 2. Schematic of Combustion Bomb and VRS Transducer.

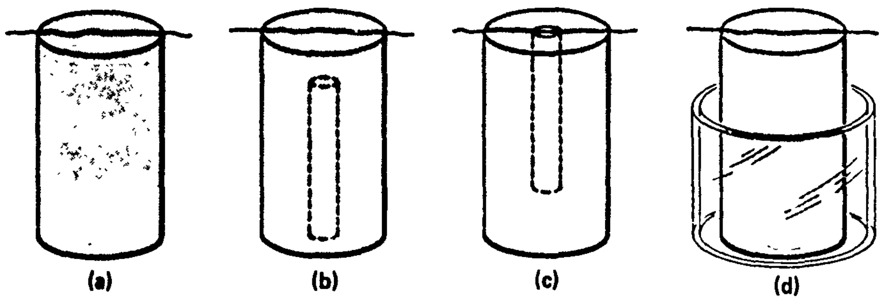

FIGURE 3. Flashdown Test Geometries.

PRELIMINARY EXPERIMENTS

Having established the characteristic VRS spectra for plain cigarette-burning and for flashdown, FKM was chosen as a baseline propellant since a great deal of information on this propellant existed in the literature. A series of NWC research propellants[4] (ALTU series) having systematic variations of ingredients was also examined, as well as VMX-2J (a Joint Venture propellant).

Figure 4 shows the root-mean-square VRS spectra of solid cylinders of FKM propellant at three different test pressures. This example is of straightforward cigarette-burning with no flashdown. Figure 5 shows the rms spectra of FKM samples with flashing into open pores after cigarette burning for a brief interval. For example, the step on the leading edge of the major peak registers the brief cigarette-burning prior to burn-through into the pore and the subsequent flashdown. Figure 6 shows the VRS spectra of three samples of FKM which are the reverse of the geometry of Figure 5 (i.e., the strand is up-ended and ignited at the mouth). In this instance the pore is actually blind but combustion begins with the pore pressure equal to the bomb pressure.

Considering the spectra of Figure 6 in order of increasing pressure, it may be seen that the slope of the envelope changes from a decaying signal at 200 psi (1.38 MPa) to an increasing one at 600 psi (4.14 MPa). This series is representative of partial burning in the pore which progresses to a full flashdown. The progression of partial ignition or internal cratering is depicted schematically in Figure 7. The spectra in Figure 6 correlate with the burning geometries in Figure 7. The peak, marked by an asterisk in Figure 6a, is representative of combustion just beginning inside the mouth of the pore.

The significant conclusion to be drawn from such a series is that there may be a series of stages between no flashdown and fully developed flashdown in which the ambient pressure is too low for flashdown at that diameter and in which it is possible to burn in the pore without the runaway burning rate developing. It is possible for the strand to burn in the fashion of Figure 7b until the bomb pressure is raised (by combustion gases) to the critical value for that pore diameter, at which time the runaway flashdown ensues. If the strand has regressed to the point that no pore remains at the point the critical pressure is reached, obviously no flashdown is possible.

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[4]Naval Weapons Center. *The Formulation and Combustion of the ALTU Propellants Prepared at NWC in Support of the High Energy Propellant Safety (HEPS) Program*, by R. M. Price, and others. China Lake, Calif., NWC, April 1976. (NWC TM 2765, publication UNCLASSIFIED.)

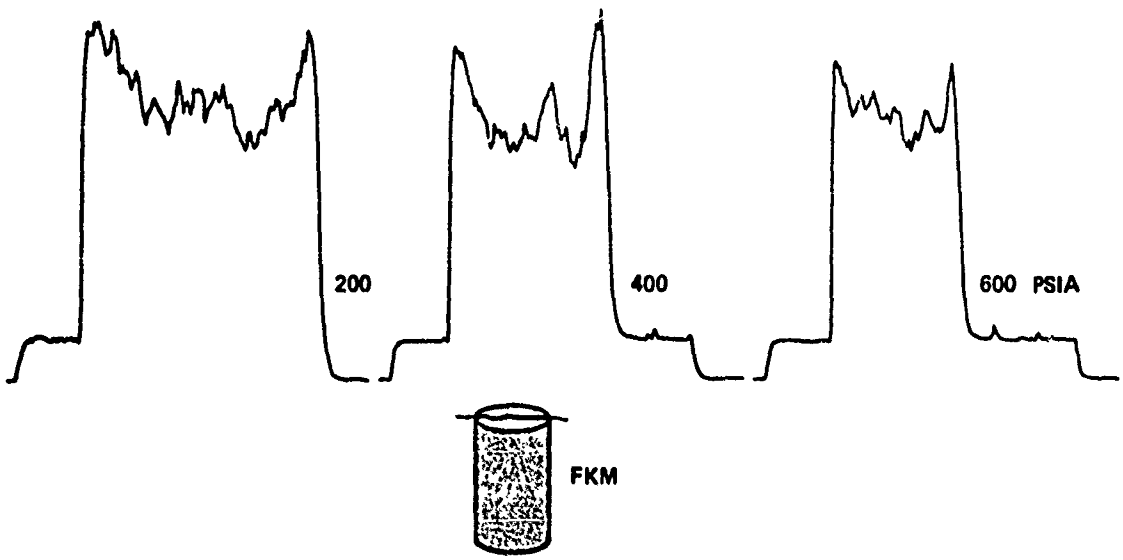

FIGURE 4. Cigarette Burning: Baseline VRS.

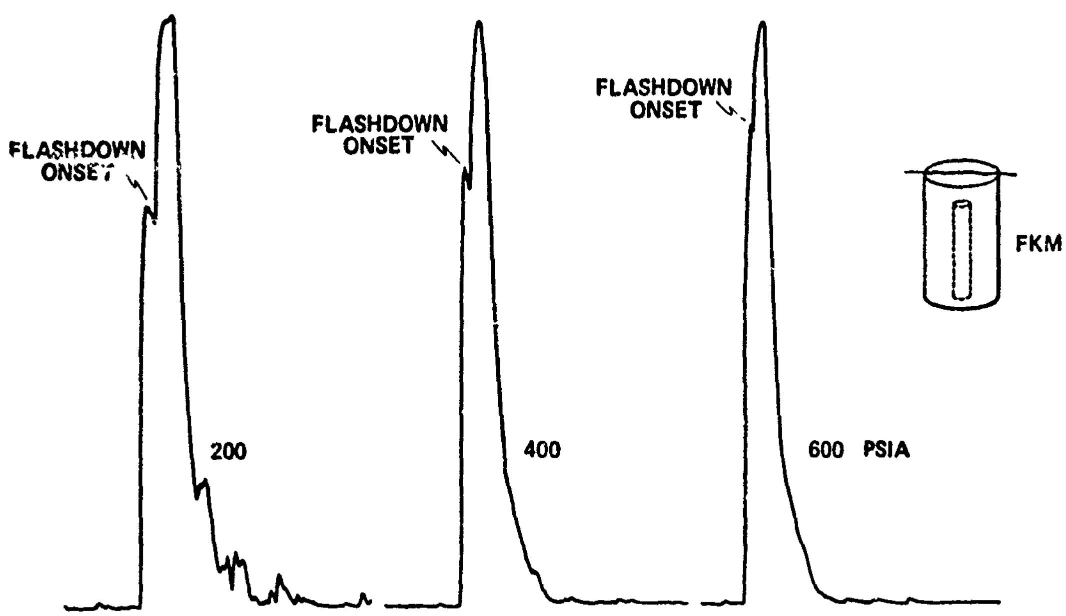

FIGURE 5. Open Pore: Vigorous Flashdown.

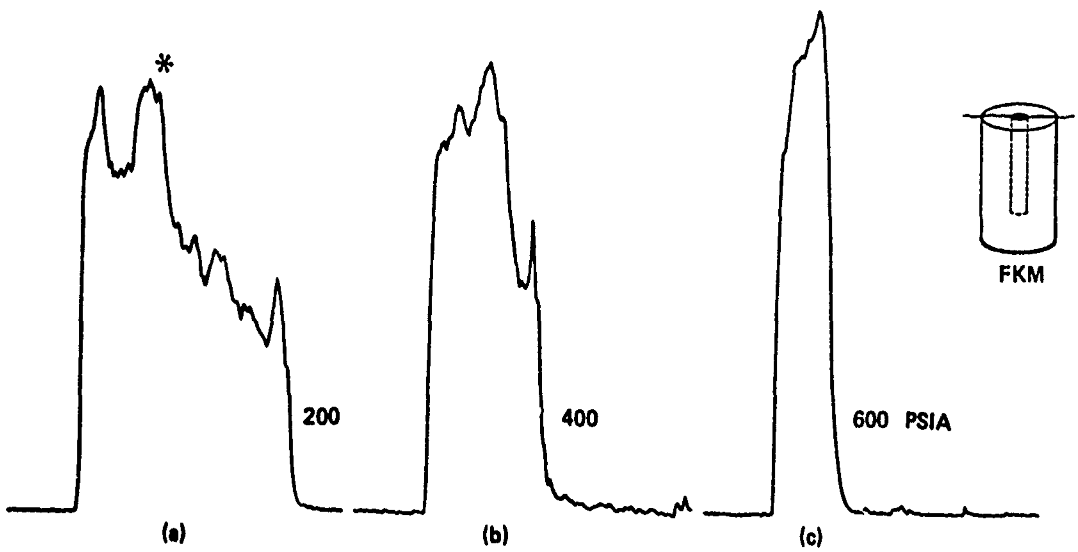

FIGURE 6. Blind Pore: Cratering at 200 and 400, Moderate Flash at 600 psia. Relative amplitudes are significant and all specimens plotted on same time scale.

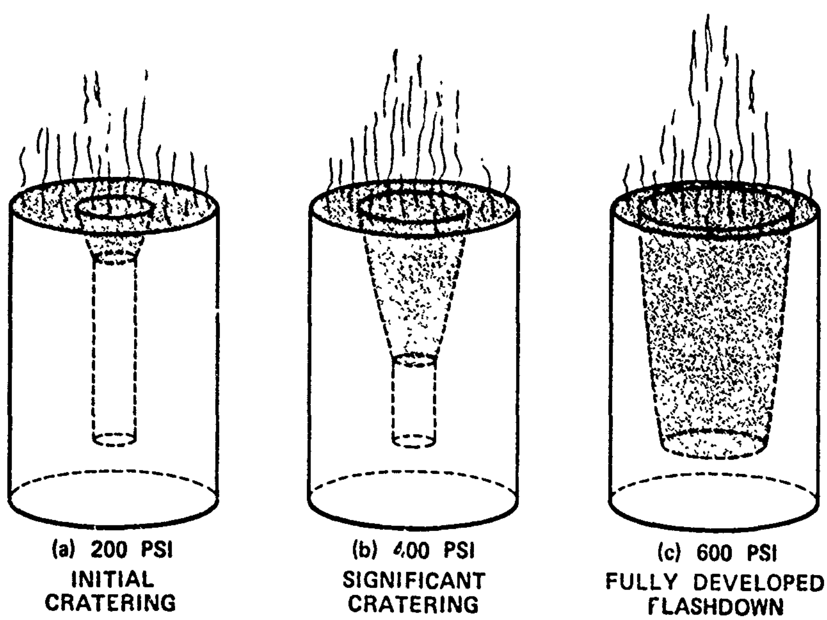

FIGURE 7. Subcritical Flashdown Conditions, Shaded Areas Burning.

Figure 8 shows the effect of combustion in an annular flashdown geometry which corresponds to the case-unbond situation in a rocket motor. In these tests a solid cylinder of propellant was placed in the sample holder and a loose fitting glass tube dropped over the strand. As can be seen from the figure appreciable propellant protrudes from the top of the glass to ensure ignition and a small amount of steady-state cigarette-burn before flashdown into the annulus. No inhibitors were used on the propellant. Although the bottom of the annulus is closed in these tests the situation does not equate with a blind pore. In this case the flashdown does not propagate uniformly down the surface of the cylinder, but instead, the ignition front (and the combustion gases) swirl around and downward. There is virtually no difference between the spectra here and in Figure 5 except for the duration of events. The cigarette-burning phase is longer for the annular cases because more propellant protruded from the glass than was available for the tests in Figure 5. This test configuration is geometrically blind but not hydrodynamically blind.

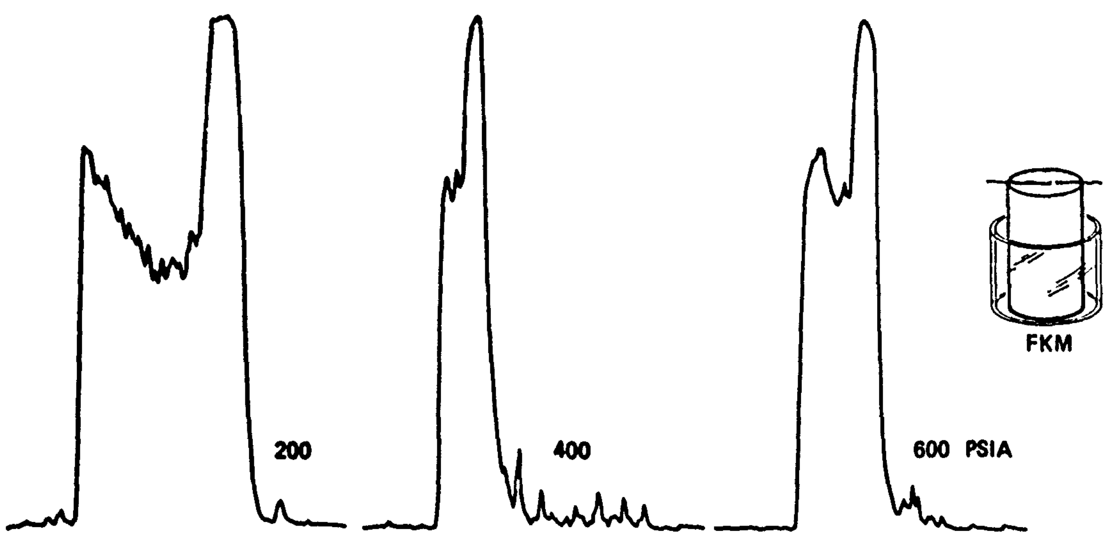

FIGURE 8. Nominal 0.80 mm Diameter Difference: Vigorous Flashdown.

PORE PRESSURE MEASUREMENTS

Some rudimentary efforts were made to measure pore pressure during the course of the burning, including the flashdown. The experimental arrangement can be seen in Figure 9. In these tests a 50-psi (345-kPa) differential pressure transducer was mounted in the sample holder to measure what might be called head-end pressure. An exhaust port was provided which could be opened or closed to suit the circumstances being tested (i.e., open- or blind-pore burning).

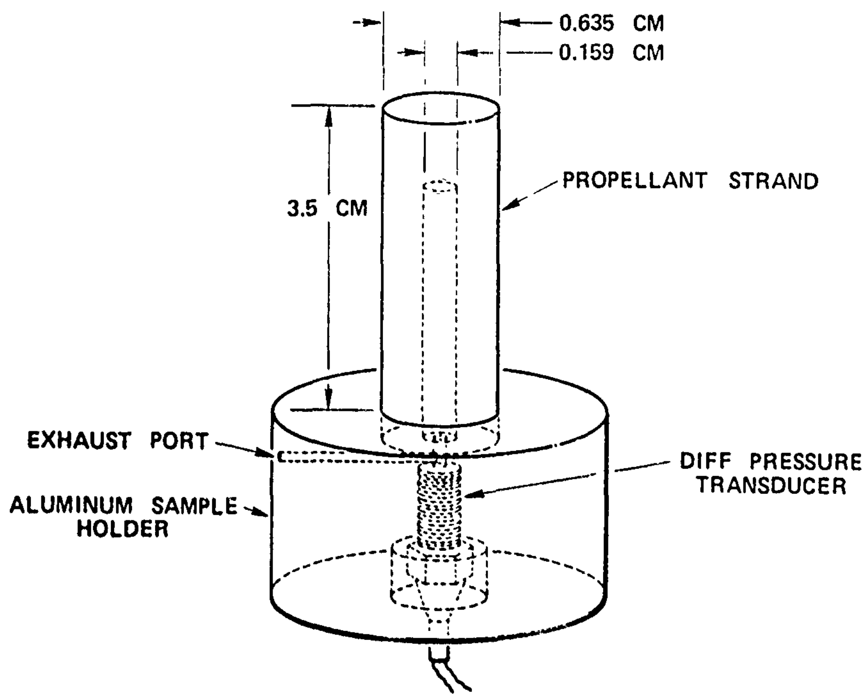

FIGURE 9. Test Set-Up for Measuring Pore Pressure.

Figures 10 and 11 are composite figures showing the VRS spectrum and the simultaneously measured pore pressure for samples of PNC-PETRIN propellant. The reproducibility of these two specimens is excellent. The apparent difference in pressure traces is due to difference in amplifier gain on the plotter.

Figure 12 shows the composite VRS and pressure trace for a specimen of ALTU-5 propellant which did not flashdown. Note the absence of any pore pressure and the characteristic VRS signal indicating no flashdown.

Other pore pressure tests were done with the test geometry shown in Figure 13. Here the pre-ignition geometry resembles a macaroni grain. A PNC-PETRIN propellant strand burned in this configuration yielded the representative composite data shown in Figure 14. The waveform of the VRS and the differential pressure record, though quite different from the partially perforated grain, are characteristic of this geometry and are quite reproducible. Figure 15 compares the VRS and pressure records for representative systems examined here. Table 1 summarizes the limited pore pressure measurements. This aspect of the flashdown in pores was not pursued further because the test geometry led to unacceptably high attrition of differential pressure transducers due to flame impingement on the diaphragm. (RTV coatings and silicone grease columns proved inadequate).

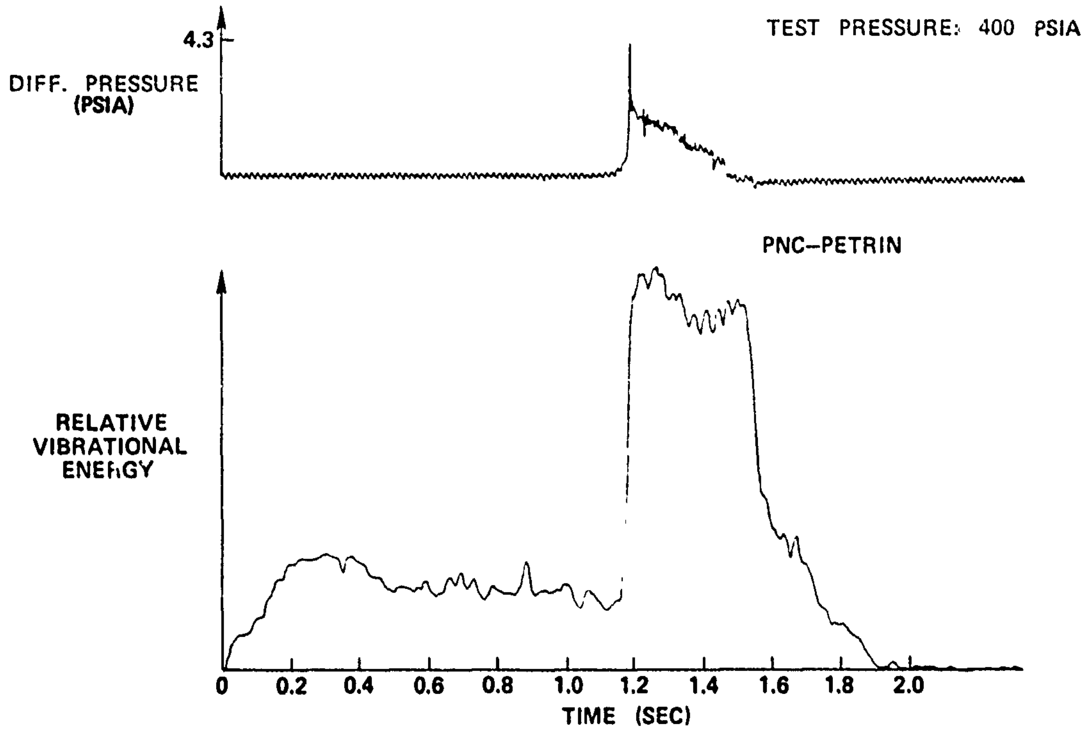

FIGURE 10. Simultaneous Pore Pressure and VRS for Double-Base Propellant.

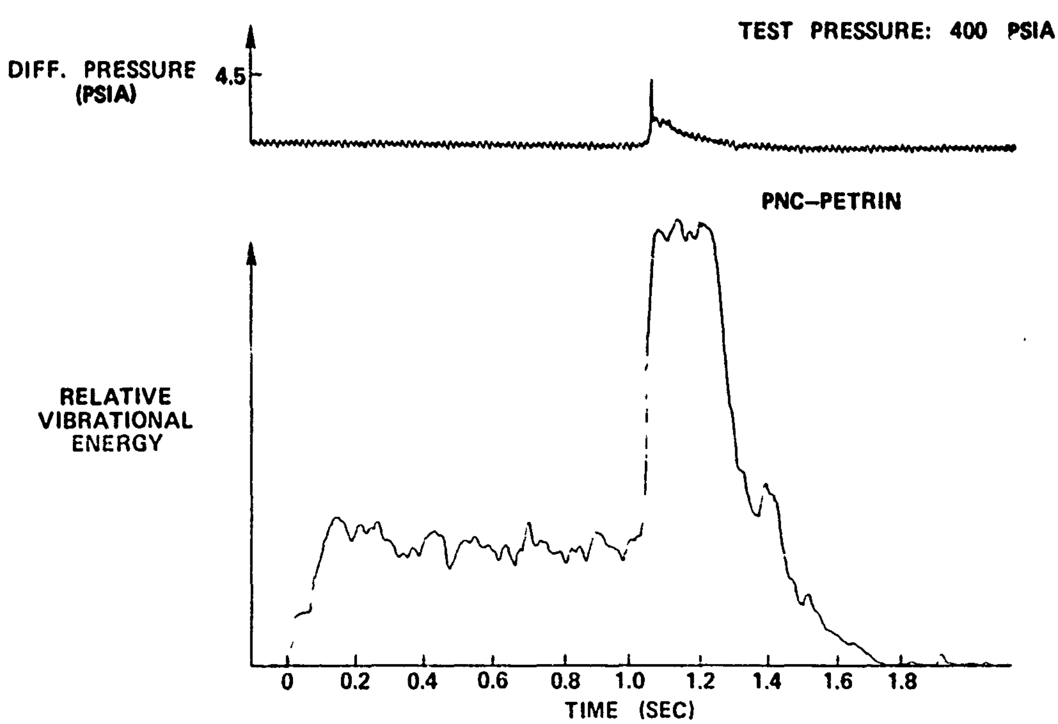

FIGURE 11. Simultaneous Pore Pressure and VRS for Double-Base Propellant.

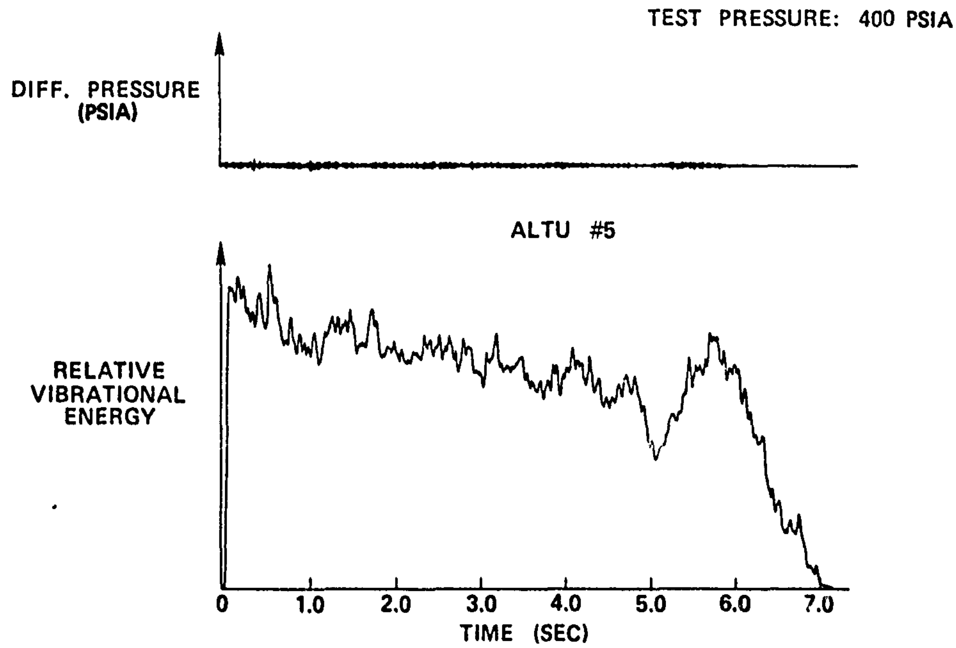

FIGURE 12. VRS and Pore Pressure Measurements on ALTU-5.

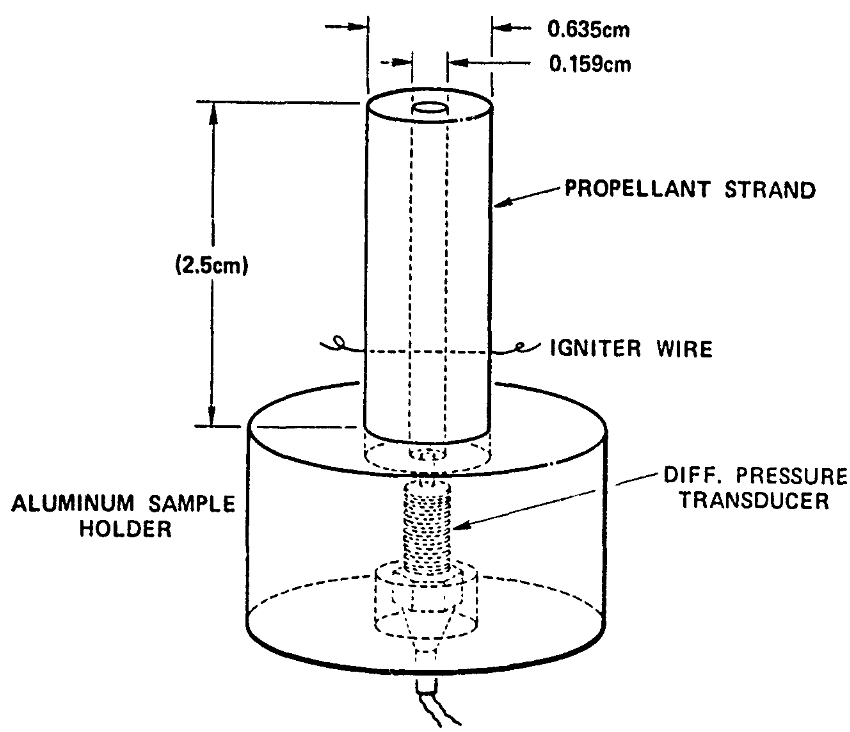

FIGURE 13. Alternate Test Geometry for Measuring Pore Pressure.

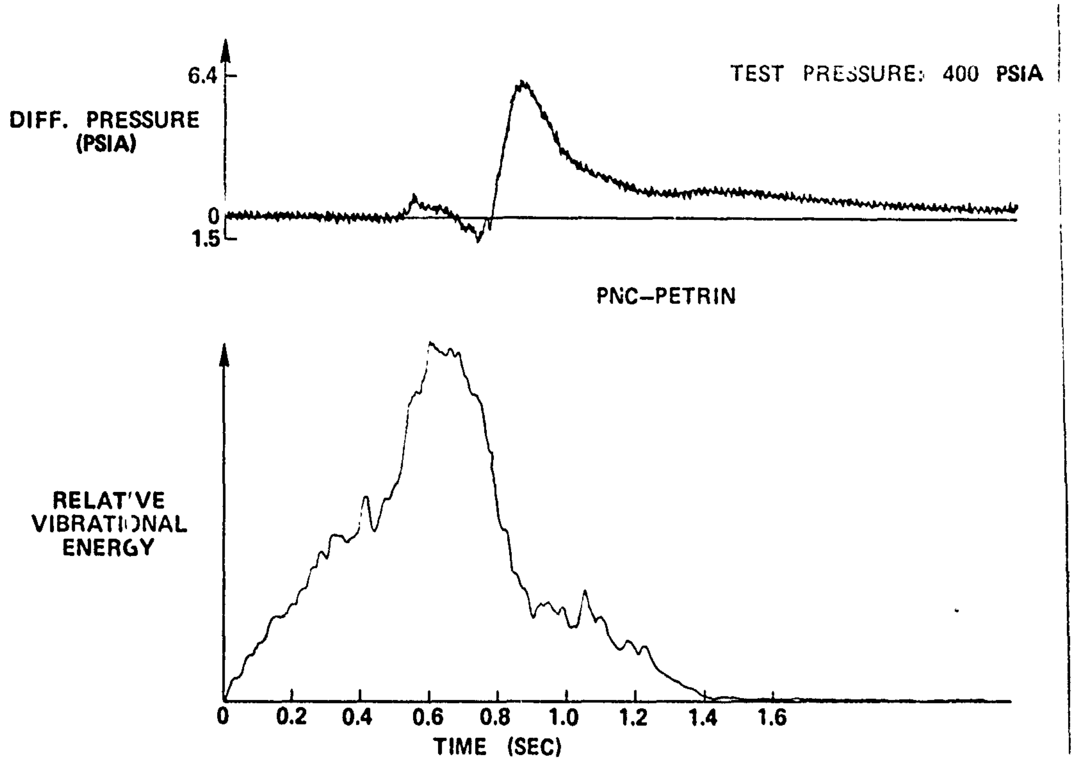

FIGURE 14. Pore Pressure and VRS for Macaroni Strand of Double-Base Propellant.

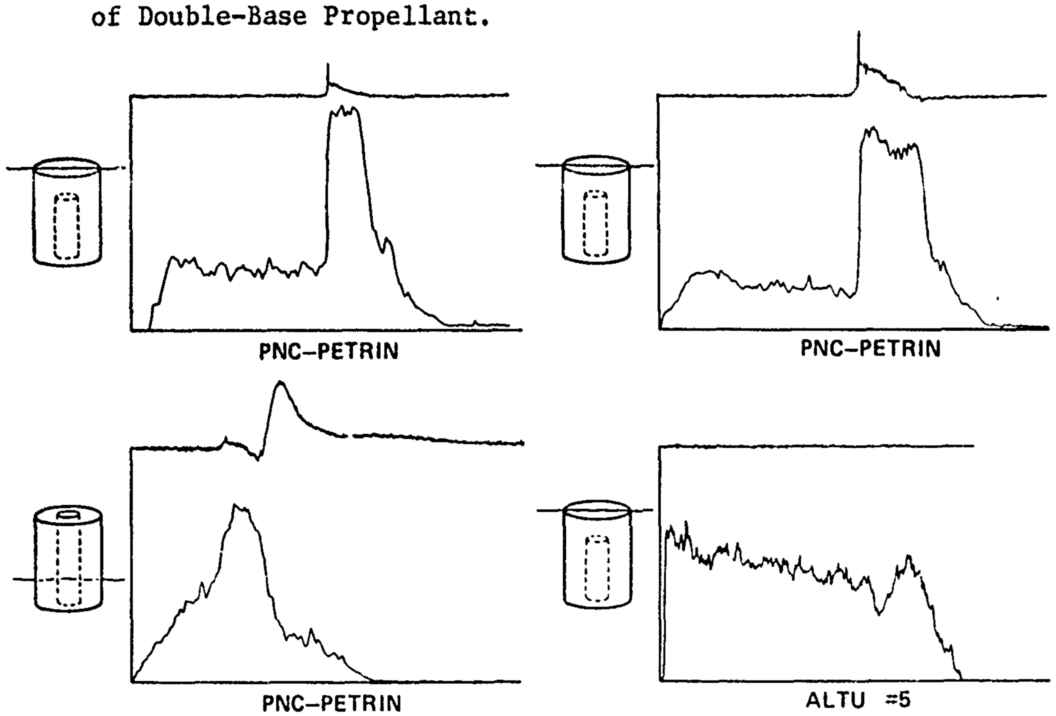

FIGURE 15. Composite Data for Simultaneous Pore Pressure and VPS on Several Different Propellants and Test Geometries. All samples burned at 400 psia. Top two specimens are replicate experiments.

TABLE 1. Differential Pore Pressure Accompanying Crack Burning (psi).[a]

Propellant	Pore diameter, mm	Bomb pressure, psi (MPa)	Geometry	
			As in Figure 9	As in Figure 13
FKM (Blend 265)	1.59	200 (1.38)	...	1.47, +9.0/-1.39
		400 (2.76)	1.72, 1.23	13.9, 5.11, 37.2
		600 (4.14)	...	28.2, 25.0
FKM (Blend 265)	0.79	200 (1.38)	...	...
		400 (2.76)	...	2.05/2.66, 3.77
		600 (4.14)	...	...
ALTU-5	1.59	200 (1.38)	...	...
		400 (2.76)	Zero	0.80, 1.07
		600 (4.14)	...	...
PNC-PETRIN	1.59	200 (1.38)	...	...
		400 (2.76)	4.3, 4.5	6.3
		600 (4.14)	...	...

[a]The table gives several values of peak pore pressure for each test condition indicating that replicate strands were burned.

The pore pressure tests may be summarized as follows. The test data show that ALTU-5 propellant does not flashdown under any of the conditions examined thus far. Both FKM and the PNC-PETRIN propellants flash quite vigorously. In both of the propellants which do flashdown (FKM, PNC-PETRIN), the pore pressures accompanying flashdown are higher in the macaroni strand than in the partially perforated grain. Table 1 shows that for FKM, for example, the pressures in the macaroni strand are significantly higher. Alternatively, for equal conditions of propellant type and bomb pressure, FKM pore pressure was reduced by about a factor of seven by cutting pore diameter in half (1.59 mm → 0.79 mm).

FLASHDOWN CRITICAL DIAMETER

It will now be shown that there is a critical minimum diameter for flashdown. To quantify the relationship between critical diameter and ambient pressure is vital, since one can then take steps to suppress the flashdown. A different test geometry was employed to better simulate pores which might occur in the interior of a solid propellant rocket grain. Figure 16 shows the means of fabrication of the blind pore test specimens used for the bulk of the flashdown experiments.

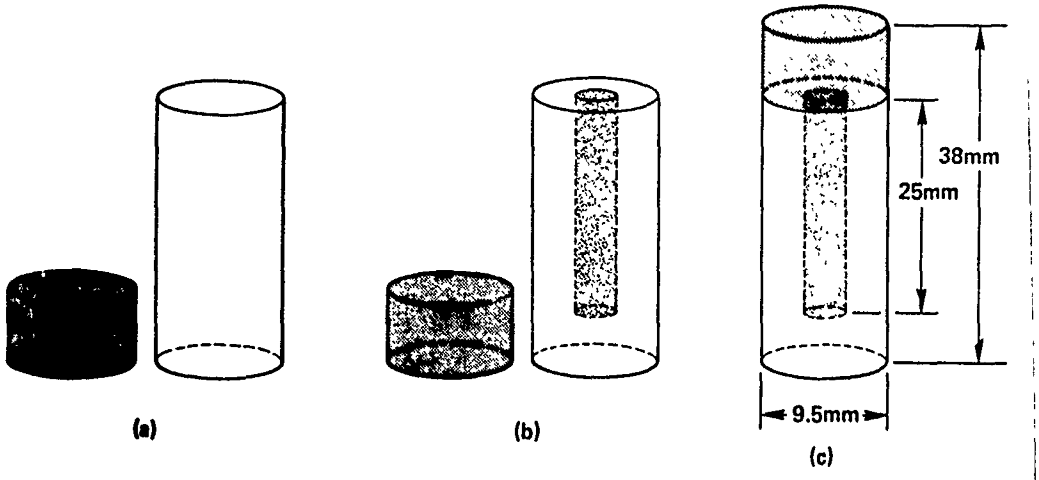

FIGURE 16. Fabrication of Blind Pore Test Specimens for Flashdown Critical Diameter.

These samples are prepared by cutting a solid cylinder from a large block of propellant by means of a cork borer. This cylinder is then cut into two pieces as in Figure 16(a). A hole of known dimensions is drilled into the longer specimen and the plug is then cemented (Eastman 910) over the mouth of the hole. By using a series of new, sharp drills which have never cut any other material, a series of pore sizes may be prepared having reasonably sharply cut walls. In some tests the pores were cast into the propellant. This was the case for all PNC-PETRIN specimens. Drilling was resorted to because it is not always possible to cast all the test propellants to the desired configurations. Moreover, in the case of the FKM, the propellant was already fabricated and no alternative to drilling existed. The effect of pore wall roughness and binder concentration gradient at the wall remain to be assessed but will be examined.

Figure 17 compares the burning characteristics of various test geometries of FKM propellant. Shown here are the test geometry and associated VRS signal from the burning. In the case of the solid cylinder no flashdown is expected and none is recorded. In Figure 17b can be seen a very vigorous flashdown in the VRS record of the blind pore. In Figure 17c there is no flashdown. The only difference between (b) and (c) is that the pore diameter in (b) is above the critical value at 200 psi (1.38 MPa), while that in (c) is below the critical diameter.

Flashdown critical diameter vs. pressure was determined for a series of test propellants and the data are shown in Figure 18. ALTU-16 propellant is included here because, during the course of this investigation, the Joint Laboratories Task Group for the HEPS program selected

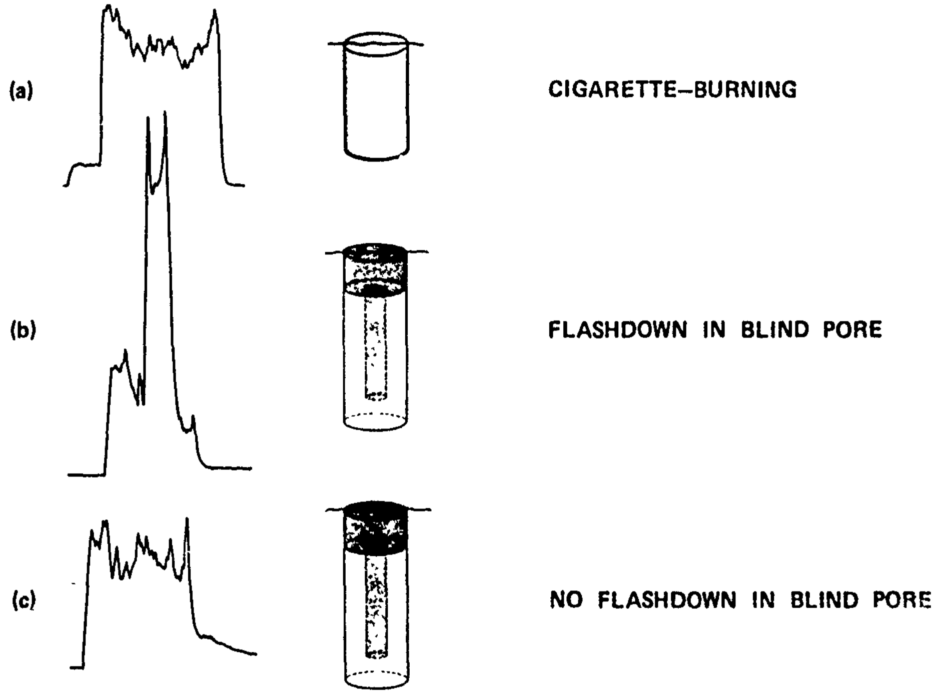

FIGURE 17. FKM Burned at 200 psia.

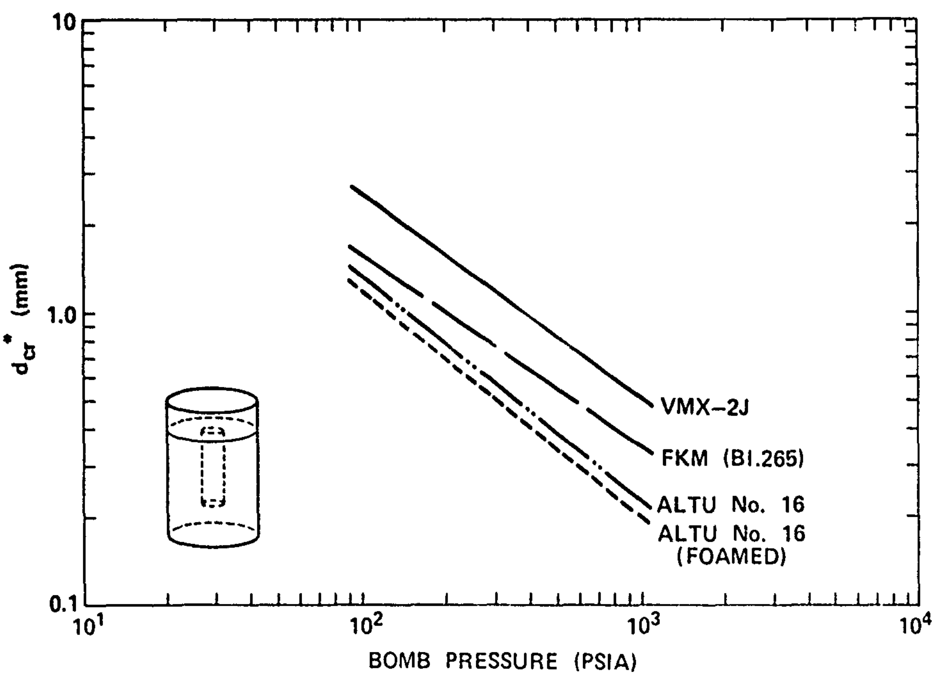

FIGURE 18. Flashdown Critical Diameter vs. Pressure for a Series of Test Propellants.

it as the baseline propellant for the program. The ALTU-16 foamed propellant was prepared by adding water to the binder during cure to produce voids in the material.[4] This technique yielded a material with 10.9% voids. The resultant propellant thus contained a significant fraction of unconnected pores. It also results in a small but significant (outside the data scatter) change in the flashdown susceptibility as seen in Figure 18. No differences in the combustion mode could be detected by VRS. The VRS signals from two such specimens are compared in Figure 19.

The flashdown critical diameter vs. pressure for open and blind pores in VMX-2J propellant is shown in Figure 20. While a direct comparison between the combustion conditions is not possible in these two cases, the dramatic difference in flashdown susceptibility can be readily seen. It needs to be noted, however, that the entire pore in the open pore case is full of cold gas and is at bomb pressure at the instant of ignition in the pore, whereas the blind pore is at atmospheric pressure. Thus, neither the heat transfer nor hydrodynamic conditions are the same.

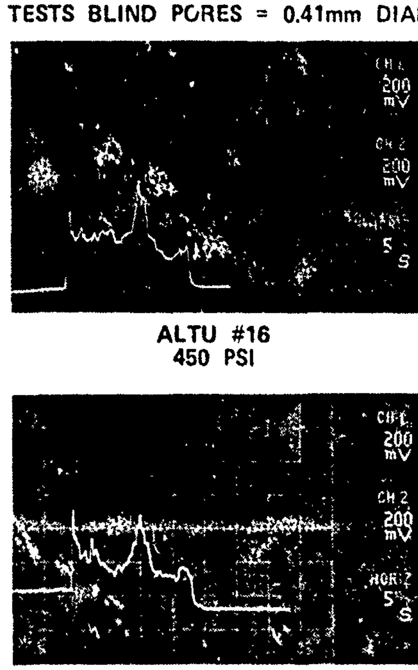

FIGURE 19. Comparison of VRS Signals from ALTU-16 and ALTU-16 (Foamed). Weak flashdown in both cases.

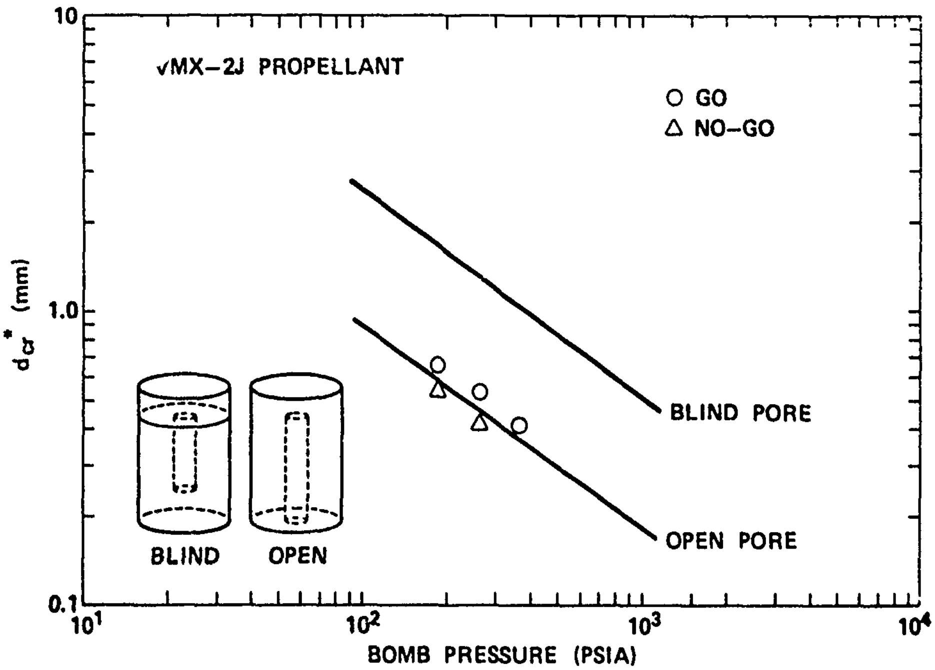

FIGURE 20. Comparison of Flashdown Critical Diameter vs. Pressure for Blind and Open-Ended Pores in VMX-2J.

The same type experiments that produced the data of Figure 20 were done using FKM and the data are shown in Figure 21. This test series is not complete since the available propellant was exhausted before the master curve for the open pore case could be completely defined. Further work is required here. Note, again, that flashdown occurs more readily in the open pore than in the blind pore. The only significant difference revealed by the root-mean-square VRS signal is the much greater amplitude of acoustic emission from the open pore specimens.

EFFECT OF STORAGE/AGING ON FLASHDOWN SUSCEPTIBILITY

It was during an investigation of the effect of changes in pore L/D ratio that a dramatic difference in flashdown susceptibility of different production lots of FKM propellant was revealed. Since the pore burning experiments here equate in many ways with nozzleless rockets, it was thought to be worthwhile to see if the combustion parameters of flashdown into pores would scale with L/D as do nozzleless rockets.

To test the effect of L/D ratio, a series of FKM propellant strands was prepared according to the scheme represented in Figure 22. Three groups of strands were prepared having a series of pore lengths for a fixed diameter. The diameters chosen were: 1.0, 0.60, and 0.41 mm. Thus, each group of one diameter would have all the lengths shown in the figure. The complete group was arranged to yield L/D ratios ranging from 5.8 to 63, which was believed to be adequate to assess L/D effects on flashdown.

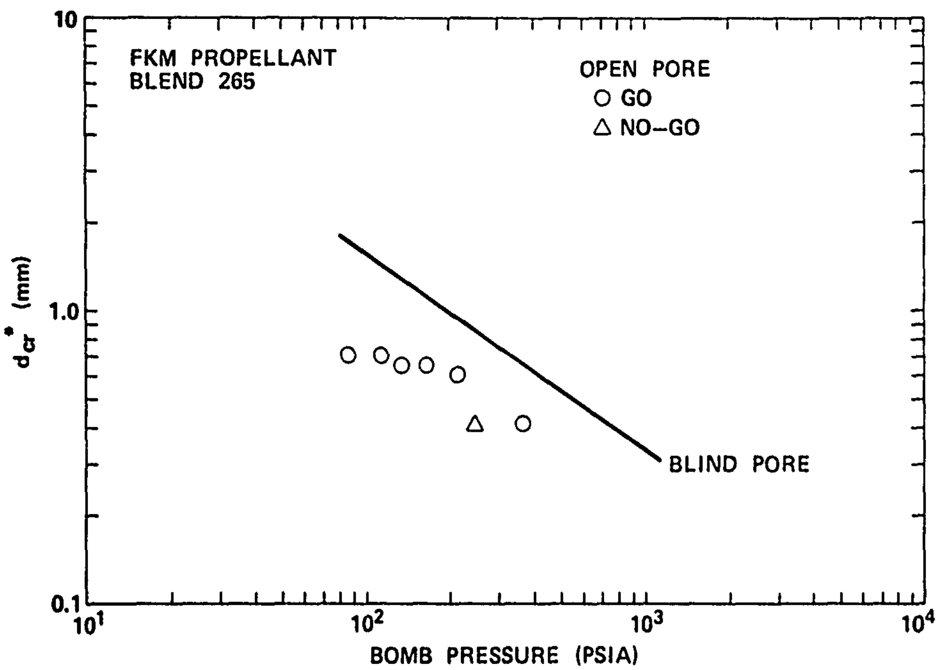

FIGURE 21. Comparison of Flashdown Critical Diameter vs. Pressure for Blind and Open-Ended Pores in FKM.

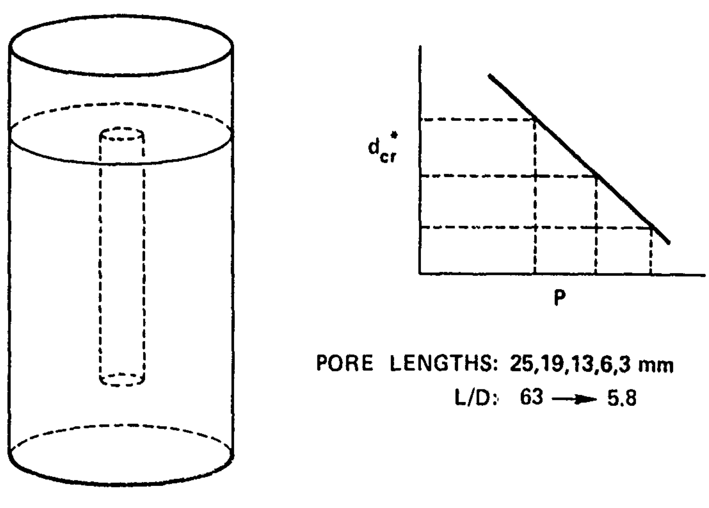

FIGURE 22. Test Conditions Established for Determining Effect of L/D Ratios on Flashdown.

The intent during these experiments was to select a series of strands of fixed pore diameter, to begin burning a series at a pressure just high enough to assure flashdown, and then begin reducing the pore length, all else being held constant. The tests were to begin with the longest pore length and progressively shorten it to see if flashdown ceased. If the flashdown failed at some particular L/D it was then planned to double the pressure and repeat the series.

The very first strand burned in this series failed to flash at the pressure where it should have flashed as determined in previous studies (Figure 18). Other samples in the same pore diameter were tried at higher and higher pressure without success. Another pore diameter group was selected and burned, and again, no flashdown. It became clear at this point that something was dramatically different about the propellant, since a thorough check of the apparatus and data acquisition revealed no anomalies.

Further investigation of this point disclosed that the original quantity of FKM (Blend 265) with which these trials had begun, had been exhausted and another production lot (Blend 269) substituted by the magazine personnel. Since Blend 269 had also become scarce at this point, two other lots were acquired (FSD-6-5, FSD-6-6) and single strands were burned for comparison with those described above. Figure 23 compares the data on all the above propellants. All the triangles in this figure represent non-flashdowns under conditions where the material should flash. The line represents the master curve for the original material employed in these experiments. One sample each of FSD-6-5 and FSD-6-6 were tried and are seen superimposed at 250 psi (1.72 MPa). Thus, none of the three subsequent lots would flash where Blend 265 had flashed.

Inasmuch as the apparatus had been shown to be functioning adequately, it was assumed that a difference in the propellant characteristics had to be present. To discover the nature of the discrepancy, several types of experiments were performed on these four production lots of FKM. Xenon arc-image ignitability tests at 150 psi (1.03 MPa) nitrogen pressure were performed on all four lots. The data are shown in Figure 24, where the data scatter is hidden within the size of the circular symbol in two out of three cases. These tests reveal no difference in arc-image ignitability.

The VRS spectra of the four lots are compared in Figure 25, where it can be seen that Blend 265 flashes at 200 psi (1.38 MPa) while none of the other three does so, even at higher pressures. The spectrum of each specimen differs from the others.

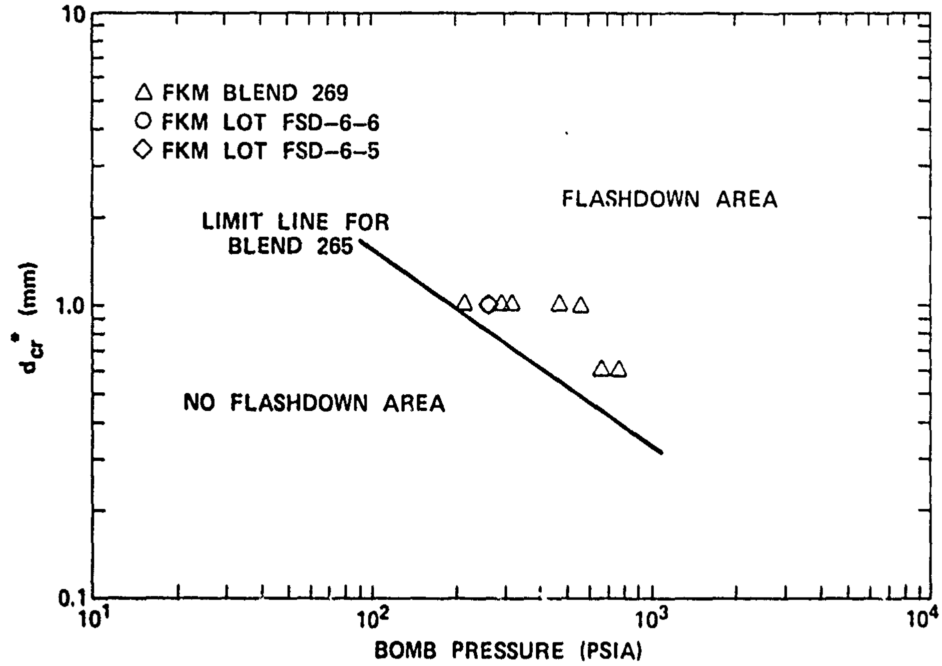

FIGURE 23. Flashdown Critical Diameter vs. Pressure Showing Failure to Flash of FKM Lots Other than Blend 265.

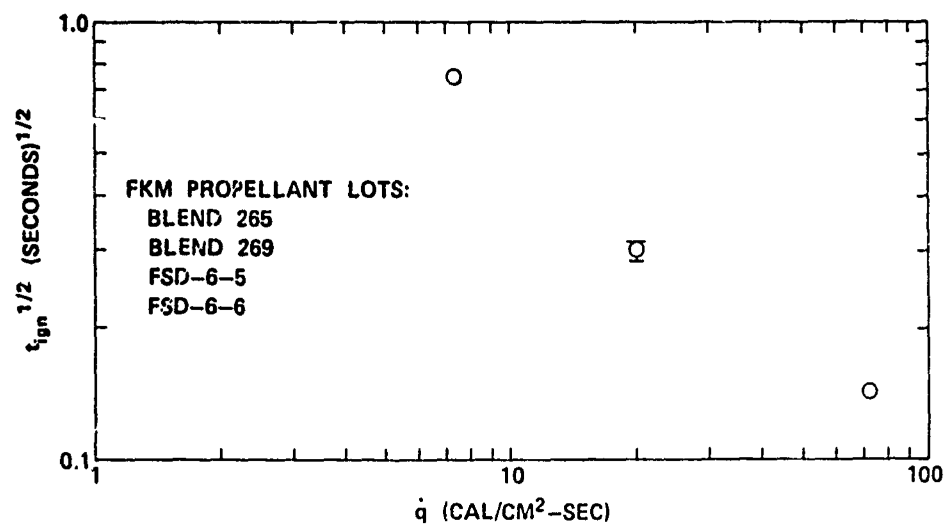

FIGURE 24. Arc-Image Ignition in 150 psi Nitrogen. Data scatter less than symbol size.

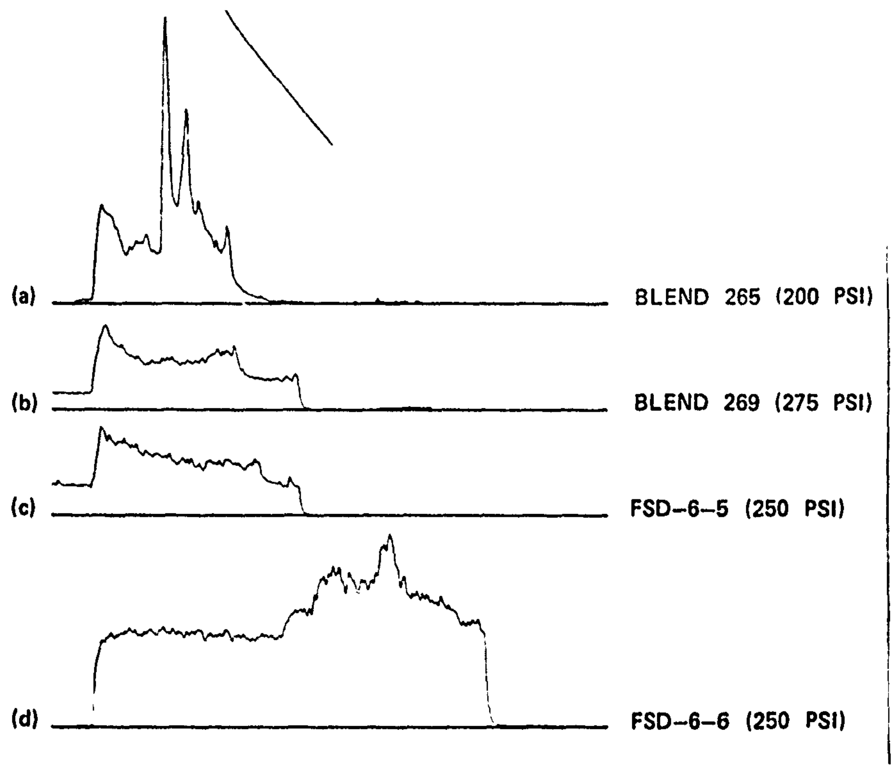

FIGURE 25. Vibrational Response Spectra of Four Different Production Lots of FKM Propellant.

The discrepancy between otherwise identical production lots of FKM prompted further tests to generate new master curves of critical diameter vs. pressure. The data in Figure 26 clearly reveal a dramatic difference in flashdown susceptibility between lots as evidenced by the significantly different curves for critical diameter. The curve for Blend 269 does not appear on the plot since the supply of 269 was exhausted before the trials could be completed. However, the critical diameter curve for Blend 269 lies near that for lot FSD-6-6 as can be surmised by reexamination of the data in Figure 23.

This discrepancy in flashdown behavior for various FKM lots has such important ramifications that further effort was expended to more clearly identify the history and composition of these FKM propellant lots. It was subsequently learned that propellant lots FSD-6-5 and FSD-6-6 were cast by Hercules, Inc. from casting powder supplied by NOS/Indian Head. This casting powder was from Blend 249. The FSD lots were received at NWC in September 1973. Thus, we have four production lots of FKM propellant (Blend 265, Blend 269, FSD-6-5, FSD-6-6) cast from three different blends of casting powder, all of which met the same nominal acceptance criteria and all, so far as can be determined, stored under similar conditions in the magazines. However, since the laboratory samples used in these tests were remnants of 40-lb (18-kg) charges used for combustion instability tests in other programs, it is impossible to stipulate that storage conditions were identical.

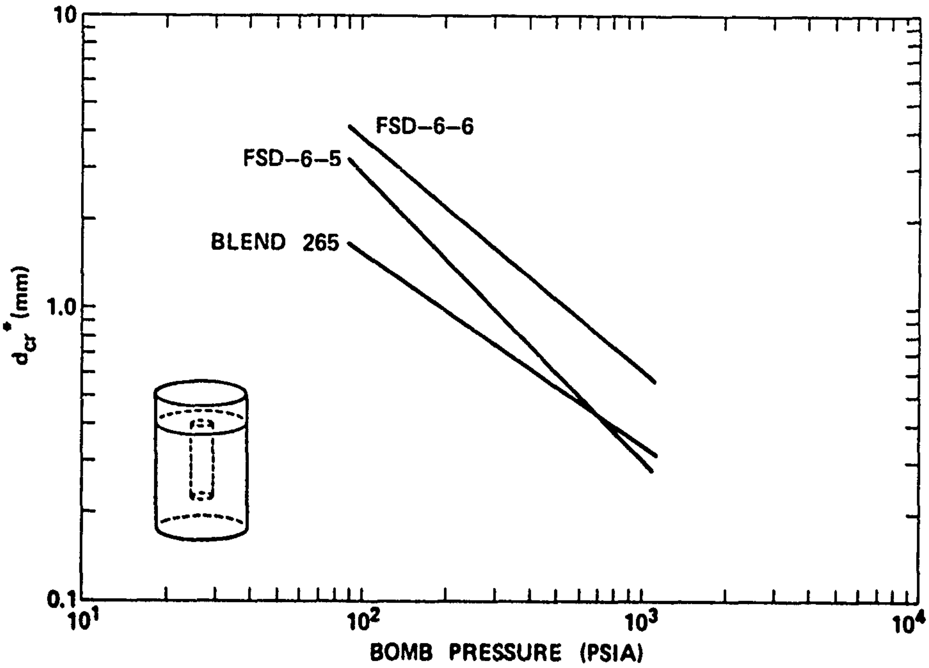

FIGURE 26. Variation in Flashdown Susceptibility for Several Production Lots of FKM.

MULTI-PORE CHARGES

As part of the test effort to span conditions from ultra-simple to complexity approximating damaged or porous propellant, multi-pore charges were prepared by drilling several pores in the same strand. The multi-pore strands were fabricated in two styles shown in Figure 27. In one case (a) all pores are the same length; in the other (b), all pores are of different lengths. In the latter case this resulted in a limited L/D series with L/D ranging from 15-31. No effect of L/D ratio was found in this range for either open or blind pores over the pressure range 300-500 psi (2.07-3.45 MPa). Typical dimensions for this series are as shown in Figure 28. Comparative VRS spectra are shown in Figure 29. Ignoring the ignition spike on these spectra, it can be seen that the VRS does very well at tracking multiple flashdowns. These four records indicate graphically the difference in intensity of acoustic emission between open and blind pores.

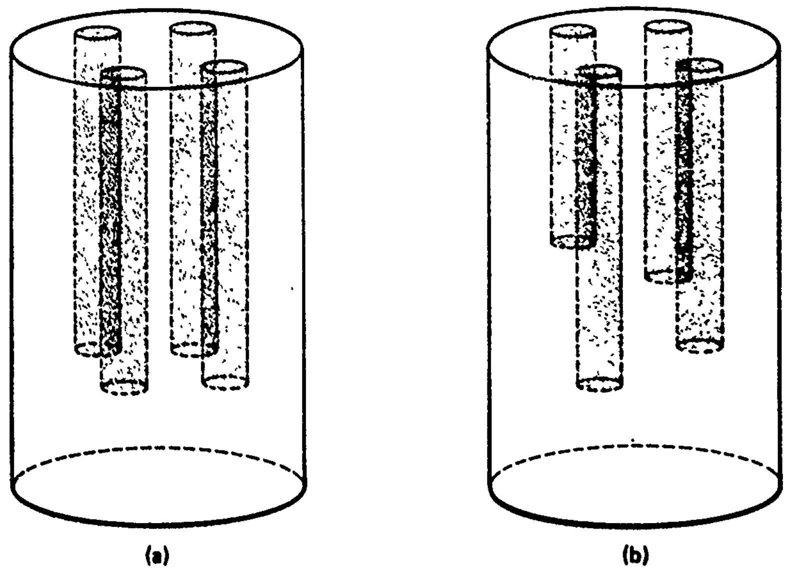

FIGURE 27. Test Geometries for Multi-Pore Flashdown Studies.

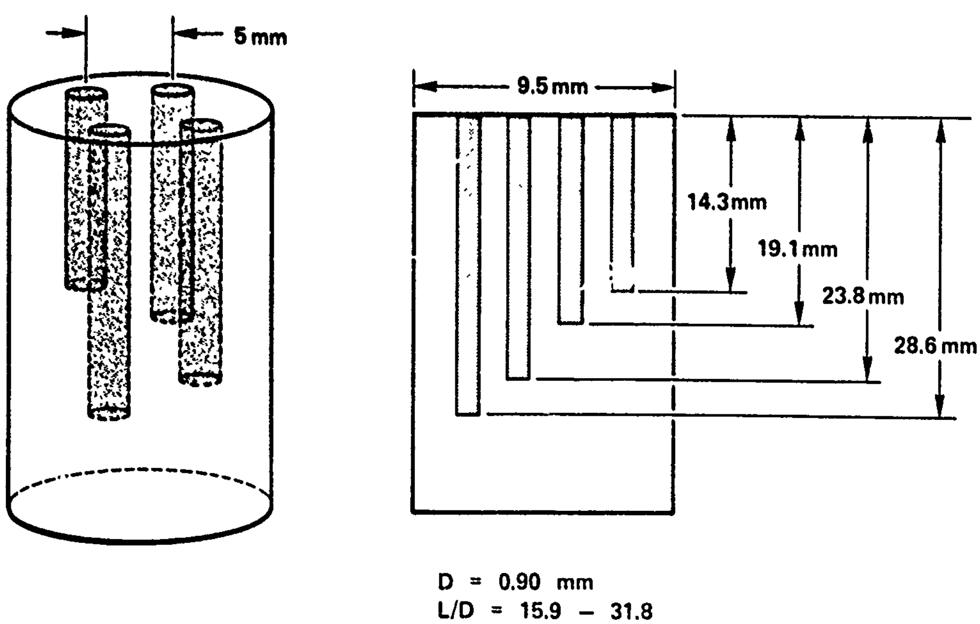

FIGURE 28. Structure of Uneven-Length Multi-Pore Flashdown Test Propellant Strand.

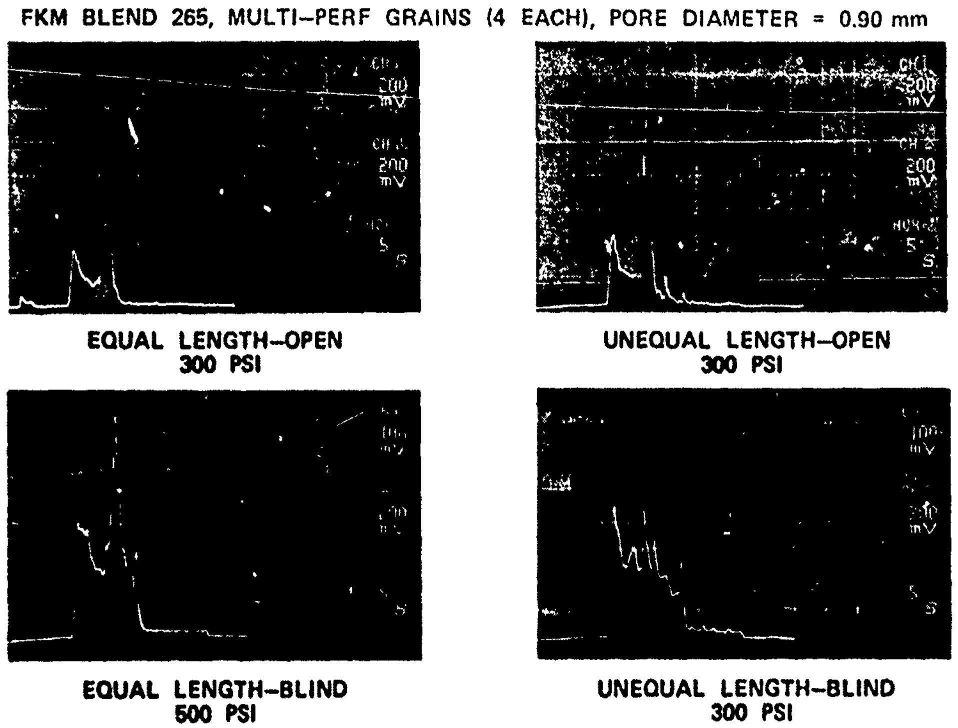

FIGURE 29. Comparison of VRS Signals from Multi-Pore Specimens Having Even- and Uneven-Length Pores.

FLASHDOWN IN "MESA" PROPELLANTS

Soviet investigators have examined the convective combustion in porous explosive charges[5] and have developed a few simple empirical correlations which tend to show a direct relationship between the burning rate and some characteristic dimension (length, width, or diameter) for flashdown. Godai has studied convective combustion in cracks and cylindrical pores in aluminized and non-aluminized composite propellants.[6] Godai has claimed that the flashdown threshold crack gap is fundamentally a function of the burning rate. He confesses immediately, however, that the simple thermal model which he offers cannot explain the behavior of aluminized propellants ($\leq$30% Al). These empirical correlations of Andreev and Godai are attractive in their simplicity but appear to fail of useful generalization. In any event, it appears important to assess the extent to which the flashdown critical dimension is a function of, or is controlled by, the burning rate.

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[5]A. D. Margolin and S. V. Chiuko. "Combustion Instability of a Porous Charge with Spontaneous Penetration of the Combustion Products into the Pores," *Fizika Goreniya i Vzryva*, Vol. 2 (1966), pp. 72-75.

[6]T. Godai. "Flame Propagation into the Crack of Solid-Propellant Grain," *Amer. Inst. Aeronaut. Astronaut. J.*, Vol. 8 (1970), p. 1322.

A rigorous test of such a hypothesis would be to select a propellant with a unique burning rate/pressure curve, as for example, N-5. This is a catalyzed double-base propellant belonging to a class known as "mesa" propellants (see Table 2 for composition). A schematic of such a burning rate curve is shown in Figure 30. Experiments were performed to determine if the flashdown critical diameter (d_{cr}*) would follow the burning rate curve. Preliminary examination of the data on critical diameter vs. pressure for the other propellants described in this study showed at least qualitative correspondence.

TABLE 2. Composition of N-5 Propellant.

Ingredients, wt.%	Nominal
Nitrocellulose (12.6%N)	50.0
Nitroglycerin	34.9
Diethyl phthalate	10.5
2-Nitrodiphenylamine	2.0
Lead salicylate	1.2
Lead 2-ethylhexoate	1.2
Candelilla wax	0.2
	100.0

Figure 31 shows the burning rate data for N-5 which we have just measured. Since the propellants are several years old it was considered necessary to generate a new burning rate curve. We are presently engaged in extending these data to 2000 psi (13.79 MPa). Figure 32 shows the flame stand-off distance vs. pressure measured from high magnification (4X) cinephotographs for the same specimens. Figure 33 shows the flashdown critical diameter vs. pressure for the same propellant.

Several conclusions are immediately apparent from an examination of these data. It can be seen that the flashdown critical diameter is smaller than the flame stand-off distance throughout the range studied, up to the point at which the curve flattens out horizontally. It also ɔears that the burn rate vs. pressure and d_{cr}* vs. pressure curves are .iprocals of each other, as suggested by the Andreev criterion.

Use of the empirical Andreev criterion (it is nothing more, since no theoretical basis for it exists) for flashdown d_{cr}* must be approached with caution, however, since it was contrived strictly for the spontaneous case of open pore and no pressure differential along the pores (i.e., pore pressure equal to bomb pressure). An expression for the critical Andreev number, A_n*, is as follows:

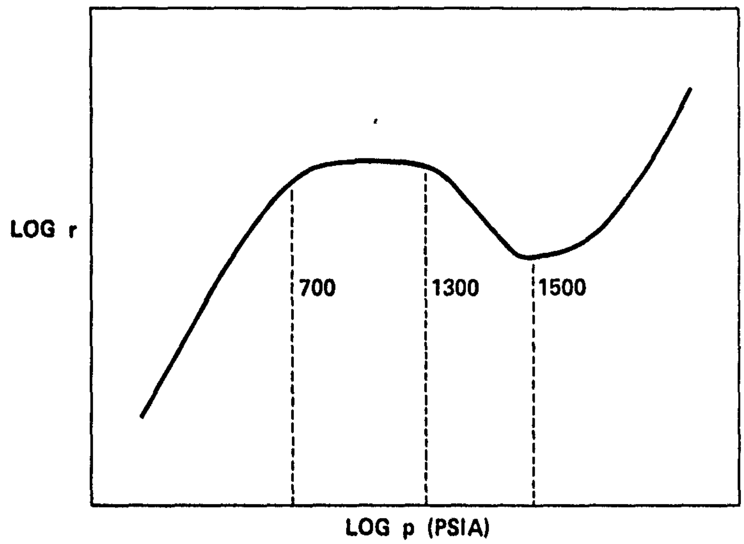


FIGURE 30. Schematic Representation of "Mesa" Burning Rate Curve for N-5 Propellant. (Slopes and inflection points change with ambient temperature.)

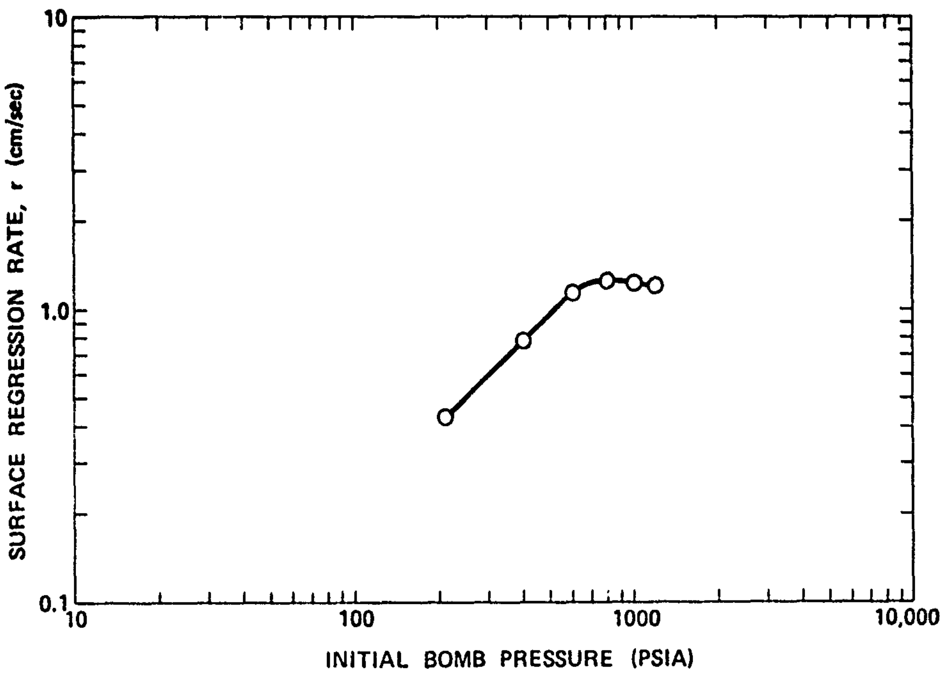


FIGURE 31. Burn Rate vs. Pressure for N-5 Propellant. (Ambient temperature = 25°C.)

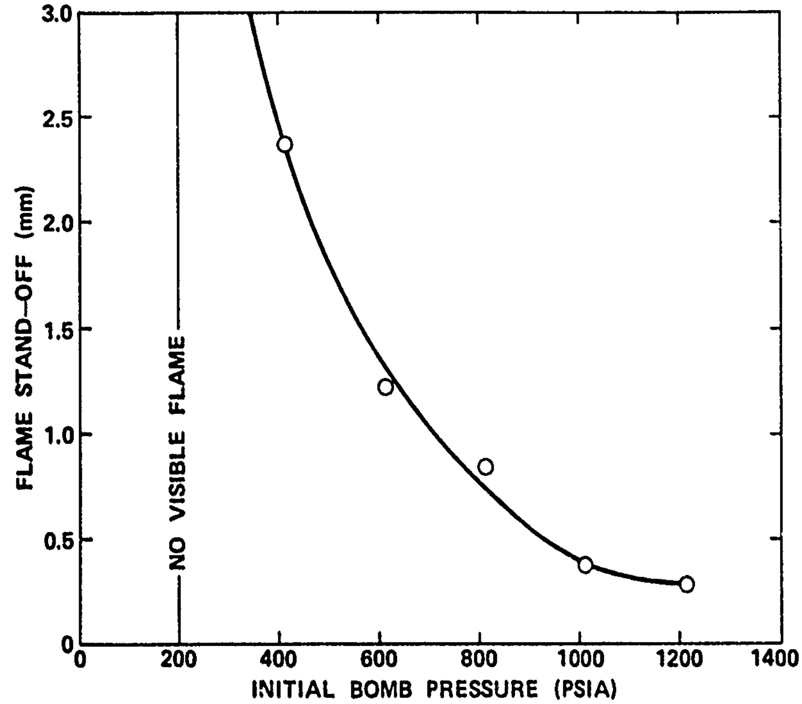


FIGURE 32. Flame Stand-off vs. Pressure for N-5 Propellant.

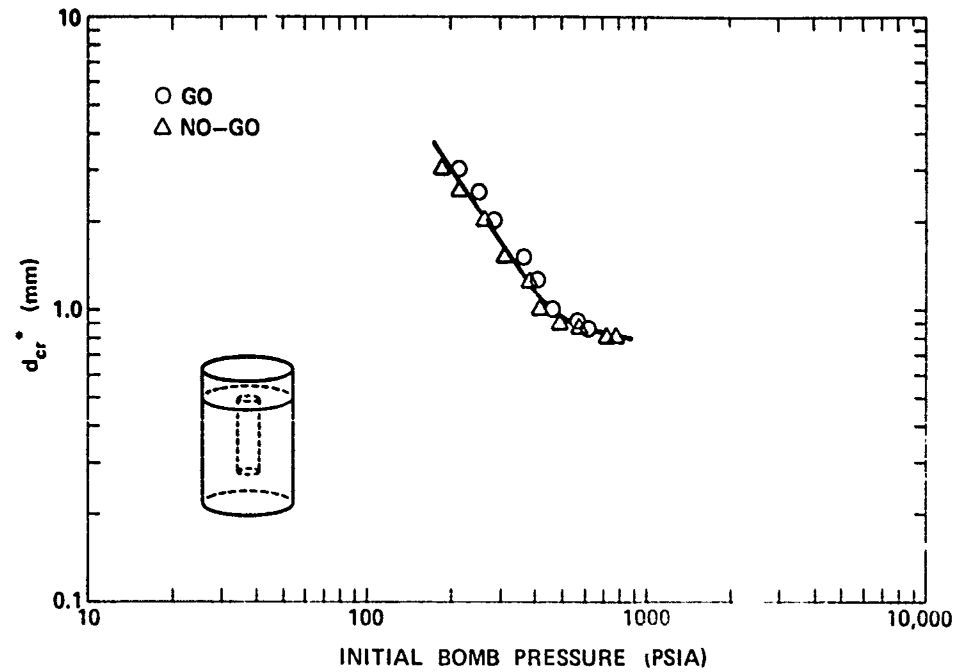


FIGURE 33. Flashdown Critical Diameter vs. Pressure for N-5 Propellant.

$$\frac{rd}{\lambda/\rho c} = \frac{aP^n d}{\lambda/\rho c} = A_n^* \qquad (1)$$

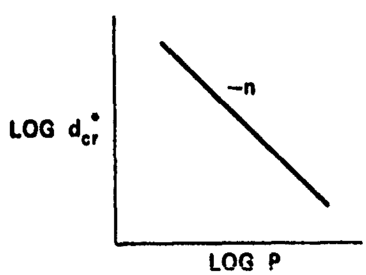
where

r = surface regression rate
d = pore diameter
P = bomb pressure
λ = thermal conductivity
ρ = solid density
c = specific heat
a = constant in burning rate expression

thus

$$P^n d = \text{constant} \qquad (2)$$

therefore



Thus a plot of log d_{cr}^* vs. log pressure should give a line whose slope is -n (the burn rate exponent). There is qualitative and near quantitative agreement for FKM, VMX-2J and ALTU-16 propellants as shown in Table 3.

TABLE 3. Comparison of Slopes of Linear Burn Rate vs. Pressure and Flashdown Critical Diameter vs. Pressure for Test Propellants.

Propellant	Burn rate exponent n	Slope of d_{cr}^* line
FKM (FSD-6-6)	0.76	-0.78
VMX-2J	0.82	-0.79
ALTU-16	0.65	-0.75

Turning back to N-5 propellant for a moment, we see that the d_{cr}* curve at first appears to be the negative reciprocal of the burn rate curve, but the agreement is less good than for the other propellants mentioned. For example, taking the slopes of the linear, lower pressure portions of the two curves gives slopes as follows: for the burn rate curve n = 0.91; for the d_{cr}* curve n = -1.22.

In cases where the Andreev criterion applies a plot of log d_{cr}* vs. log r should give a curve with a slope of -1. Treating our data that way does not yield a slope of -1, but instead yields a curve with a pronounced cusp. The complete explanation has not yet been found; however, we intend to extend the burning rate and d_{cr}* data to 2000 psi (13.79 MPa) to see if the correspondence persists throughout the mesa.

DISCUSSION

At present the modeling of flashdown or crack burning is relatively embryonic. Essentially, there are the empirical correlations of Andreev and Godai treating onset of flashdown and the theoretical model of Kuo which treats flame spread following onset.[7]

As pointed out above, the Andreev criterion is an empirical correlation, without theoretical foundation. It is contrived strictly for the case of spontaneous flashdown, meaning open pores with no ΔP in the pore except combustion-generated ΔP. The critical Andreev number, A_n* (i.e., that describing onset of flashdown), is said by Andreev, et al. to have a constant value of six. The critical Andreev number incorporates several thermophysical properties of the solid and is directly proportional to the surface regression rate of the material (page 30). Our blind pore data, while exhibiting a qualitative correspondence between burning rate and flashdown critical diameter, yields critical Andreev numbers which are neither constant nor six. Values of An* for FKM and VMX-2J ranging from 23 to 120 are found in this study. It must be borne in mind that A_n* is sensitive to the properties used and answers differing by a factor of two are possible just by selecting crystal properties on the one hand and binder properties on the other.

It would appear that asking such a simple expression as that of Andreev to describe such a complicated phenomenon as flashdown onset is asking too much. Many subtle processes are at work in the steady state burning rate of a solid propellant. Physics and chemistry are both involved in the onset of crack burning. Witness, for example, the

[7]K. K. Kuo, A. T. Chen, and T. R. Davis. "Transient Flame Spreading and Combustion Processes Inside a Solid Propellant Crack." Presented at AIAA 15th Aerospace Sciences Meeting, Los Angeles, Calif., 24-26 January 1977. (AIAA Preprint No. 77-14.)

dramatic change in flashdown critical diameter for different production lots of FKM propellant, none of which show detectable differences in arc-image ignitability. Parenthetically, the xenon arc-image furnace may not be a suitably selective measure of differences in ignitability under these critical conditions. Moreover, active species may play a critical part and thus provide the explanation for the ability of flashdown to propagate in N-5 into a pore whose diameter is less than the dark zone width and thus at a temperature less than the flame temperature.

In the work of Godai a simple thermal model is offered,[6] based on a rudimentary heat balance [Eq. (3)]. Godai claims that the threshold crack gap is fundamentally a function of the burning rate. The heat balance expression is claimed by Godai to qualitatively exhibit those features of flame propagation in a crack for a non-aluminized propellant. However, it was unable to explain the behavior of flame propagation into cracks of an aluminized ($\leq$30%) propellant.

$$t^* \propto K(T_f - T_p)/rV_pQ_R \tag{3}$$

where

t^* = critical crack gap
K = thermal conductivity
Q_R = the overall heat liberated at the surface per unit mass
r = the linear surface regression rate
V_p = propellant density
T_f = flame temperature
T_p = propellant temperature

Godai's studies included aluminized and unaluminized composite propellants, planar cracks, and drilled pores, both open and blind. His test conditions (ambient temperature, pressure from 1-4 atmospheres) appear in many instances to be marginal for the phenomena being studied, and in fact, he reports that it was impossible to induce flashdown in blind pores in any propellant studied by him even for pores as large as 10 mm in diameter. There are, however, many parallels between the findings of Godai and the results of this study. It would appear, though, that the burn rate is a parameter incapable of describing or correlating the complex phenomena which lead to onset of flashdown. Simple heat balance expressions like those of Andreev and Godai do not appear capable of useful generalization. If the governing equation for onset of flashdown only holds for certain propellant types, or for certain geometry, then it is not fundamental enough. There is a lot of complex chemistry masked by the simple burn rate concept. It would appear that the governing aspects of this chemistry will have to be unmasked.

The work of Kuo, et al.,[7] while very useful for studying the flame propagation in cracks in solid propellants, assumes ignition and treats the propagation. Thus, it is of little help in establishing the fundamental criteria for onset of flashdown.

SUMMARY AND CONCLUSIONS

To date, this study has examined the first stages of convective combustion of a number of propellants in a variety of test geometries over the pressure range 100-1000 psi (0.69-6.89 MPa). The flashdown critical diameter (d_{cr}*) vs. pressure for internal pores (both blind and open-ended) has been determined for this same series of propellants. A catalyzed double-base propellant (N-5) having a "mesa" burn rate/pressure curve has been studied to assess any correlation between burn rate and d_{cr}*.

The results may be summarized briefly as follows:

1. There exists a minimum critical diameter for flashdown into cylindrical internal pores of propellants. This diameter varies inversely with applied pressure.

2. Flashdown occurs more readily (smaller d_{cr}* for a given pressure) into open-ended than in blind pores, indicating the importance of flow processes.

3. Porous propellants (such as foamed binders with unconnected pores) are slightly more susceptible to flashdown than unfoamed propellants.

4. There appears to be a qualitative correlation between flashdown critical diameter and surface regression rate *for some propellants and some geometries*.

5. Acoustic emission techniques such as VRS can identify and track single and multiple flashdowns.

Experience has shown that flashdown is a complicated phenomenon involving chemistry, physics, gas dynamics and geometry. To claim that flashdown onset is governed by the burning rate is, in reality, to have said nothing very much. Inasmuch as we do not know the things which control the burning rate, to say that the burning rate governs the flashdown is to have explained nothing. Burning rate is too large and ill-defined a tent to be thrown over the flashdown phenomenon. Under some circumstances we find that geometrical factors exert a controlling influence; under others, that chemical properties appear to dominate. In other words, there are both necessary and sufficient conditions for onset of flashdown. Given the above, we are examining chemical, physical and geometrical factors simultaneously.

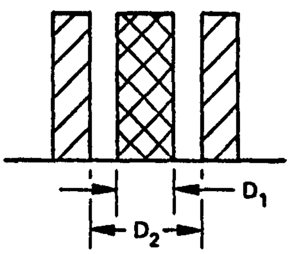
A basic aim of this study is to determine the necessary and sufficient conditions for onset of flashdown. Inasmuch as no theoretical basis yet exists for predicting these conditions, a systematic parametric study will be required before the analytical portion of the program can be advanced.

FUTURE PLANS

Since the necessary and sufficient conditions for onset of flashdown are unknown, and since no completely satisfactory theoretical criterion exists as yet, a systematic study of parameters needs to be made. The ALTU series of propellants provides a systematic variation of formulation variables which provides a unique opportunity to ascertain which parameters govern flashdown. Thus, the flashdown critical diameter vs. pressure will be determined for a series of ALTU propellants.

We intend to determine the critical flashdown hydraulic radius for the annular configuration and compare these data with those for the cylindrical blind pore and later with the rectangular cracks. Our evidence shows that flashdown into blind internal pores and into blind annuli is dramatically different. For example, for equal wall separation (i.e., 0.4 mm pore diameter and 0.4 mm wall separation in the annulus) FKM flashes into the annulus at 200 psi (1.38 MPa), while a pressure greater than 750 psi (5.17 MPa) is necessary for the cylindrical blind pore. Clearly, the annulus provides a case where the test configuration is geometrically blind but not hydrodynamically blind; inasmuch as flashdown propagates by swirling around and down the wall. Aside from providing useful insight in its own right (case-unbond analogy) the annular geometry serves as a useful transition from the cylindrical internal pore to the rectangular crack.

Several combinations of test geometry and hydraulic diameter require consideration. Calculation of hydraulic diameter for burning in an annulus presents two cases: (1) based on burning perimeter, and (2) total perimeter of the annulus. The special cases are enumerated below

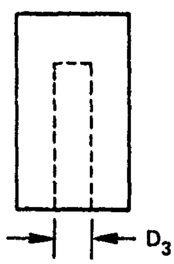


CASE 1

$$D_h = \pi/4(D_2^2 - D_1^2) / \pi D_1 \cong D_2 - D_1 / 2$$

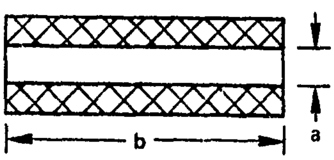
CASE 2

$$D_h = \pi/4(D_2^2 - D_1^2) / \pi(D_2 + D_1) = D_2 - D_1 / 4$$



CASE 3
ROUND HOLE

$$D_h = \pi/4\ D_3^2 / \pi D_3 = D_3/4$$



CASE 4
RECTANGULAR CRACK

$$D_h = \frac{ab}{2(a + b)} = \frac{a}{2}\left(\frac{1}{1 + a/b}\right) \quad \text{TOTAL PERIMETER}$$

CASE 5

$$D_h = ab/2b = a/2 \quad \text{BURNING PERIMETER}$$

It is possible that the critical flashdown hydraulic diameter for the annulus will be neither Case 1 nor Case 2, but some intermediate effective hydraulic diameter.

We do not suggest here that the concept of hydraulic diameter must be thought to be of overriding importance. However, it is one aspect of the problem which warrants investigation. We have already contrasted the cases of blind pores and annuli for FKM where ignitability is the same for both cases but hydraulics are not. The result is vastly differing flashdown susceptibility. Further, consider the comparison of open vs. blind pores of the same propellant where, for fixed pore diameter, the hydraulic diameter is the same in both cases but d_{cr}^* is significantly different (Figures 20 and 21).

Lastly, consider the case of porous bed combustion, which is the ultimate projection of our efforts. In their efforts to extend the concept of the Andreev criterion from the single pore to the porous bed, the Soviets[8] have used an effective hydraulic diameter based on mean pore size. The claim is made by them that the development of convective combustion in the porous bed can best be correlated by an Andreev expression employing an effective hydraulic diameter as the operative dimensional criterion. It can therefore be seen that the importance of several criteria has been established but the identification of the governing processes requires further systematic study.

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[8]V. K. Bobolev, A. D. Margolin, and S. V. Chuiko. "Stability of Normal Burning of Porous Systems at Constant Pressure," *Fizaka Goreniya i Vzryva*, Vol. 2 (1966), pp. 15-20.

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7. K. K. Kuo, A. T. Chen, and T. R. Davis. "Transient Flame Spreading and Combustion Processes Inside a Solid Propellant Crack." Presented at the AIAA 15th Aerospace Sciences Meeting, Los Angeles, Calif., 24-26 January 1977. (AIAA Preprint No. 77-14.)

8. V. K. Bobolev, A. D. Margolin, and S. V. Chuiko. "Stability ot Normal Burning of Porous Systems at Constant Pressure," *Fizaka Goreniya i Vzryva*, Vol. 2 (1966), pp. 15-20.